LLNL-JRNL-430998

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Using Intense Lasers to Simulate Aspects of Accretion Discs and Outflows in Astrophysics

D. D. Ryutov

May 10, 2010

Astrophysics and Space Science

Disclaimer

Using intense lasers to simulate aspects of accretion discs and outflows in astrophysics

D.D. Ryutov
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94551, USA
ryutov1@llnl.gov

Abstract

It is shown that some aspects of the accretion disc physics can be experimentally simulated with the use of an array of properly directed plasma jets created by intense laser beams. For an input energy between 3 and 10 kJ, one can create a quasi-planar disc with the Reynolds number exceeding 10^4 and magnetic Reynolds number in the range of 10 - 100. The way of seeding the disc with the magnetic field by using a cusp magnetic field is described.

PAC Numbers: 52.35.Ra; 52.38.Mf; 52.72.+v; 98.62.Mw; 98.62.Nx

1.Introduction

Accretion discs are a ubiquitous feature of a number of astrophysical phenomena, ranging in scale from megaparsecs to parsecs. Accretion discs are often accompanied by intense outflows along the rotation axis. Although there is no comprehensive theory explaining disc dynamics and the origin of the outflows, it is clear that the differential rotation and resulting turbulence are important ingredients of the accretion physics. It is also thought that the differentially rotating disc creates an azimuthal magnetic field which is largest near the central object and which pushes the disc material up and down in the vicinity of the axis. A necessary ingredient of this whole picture is the presence of a large (anomalous) viscosity which would determine the accretion rate. These issues have been analyzed in a number of papers over the last 20 or so years. There are reviews on this subject (Abramowicz et al, 1998; Balbus, 2003; Frank et al, 2002; Thompson, 2006) where one can find further references.

Accretion discs are typically formed around central objects pulling the matter inward by the gravity force. This – gravitational – aspect of astrophysical accretion discs is impossible to reproduce in the laboratory experiments, including high-energy-density (HED) laboratory experiments (Remington et al, 2006). On the other hand, as we show in this paper, it may be possible to recreate some other important aspects of the accretion discs by using properly arranged set of the laser-generated miniature HED jets. Specific aspects of accretion discs that may be amenable for the laboratory imitation include turbulent anomalous viscosity; interaction of differentially-rotating disc with the magnetic field, and formation of the axial outflow. As the astrophysical accretion discs are characterized by very large spatial scales, both the hydrodynamic Reynolds number and the magnetic Reynolds number are high in them. It is important, therefore, to have these numbers in the laboratory experiments as high as possible, with the hydrodynamical

Reynolds number exceeding 10^4, so as to reach the domain of developed shear-flow turbulence.

At present, a significant experience in generation of astrophysics-relevant plasma jets has been accumulated in the laser experiment (Farley et al, 1999; Foster et al, 2002, 2005; Gregory et al, 2008; Nicolai et al, 2006; Shigemori et al, 2000; Tikhonchik et al, 2008). Such jets, if replicated in the number of 6 to 9 in one shot, could be directly used for the proposed experiments. This (and even higher) number of synchronized laser beams has been routinely obtained in a number of laser experiments.

The paper contains a general description of the geometry of a possible laboratory experiment and the evaluation of the parameters of jets suitable for meaningful imitation of astrophysical phenomena. It provides an initial scoping analysis and identifies the possible range of the parameters of the laser facilities suitable for such an experiment. The results seem to be promising and will hopefully lead to more detailed studies and experiments.

2. Basic geometry

The geometry of a possible experiment is presented in Fig. 1. Some number N of identical jets (N=9 in the figure) are simultaneously generated at equal distances R from the common center. They are directed slightly off-center, all in the same sense, thereby creating a flow which has a finite angular momentum. In the situation shown in Fig. 1a, the rotation occurs counter-clockwise. The direction of the jets can be characterized by the angle ϑ measured from the direction pointing exactly to the geometrical center in Fig. 1.

The angular divergence α of the jets has to be small, so that they would not overlap in the vicinity of the injection points. We assume that $\alpha < 2\pi / N$. The radius R and the angles α and ϑ determine the characteristic external radius a of the rotating disc (or, sometimes, ring, see below) formed by the merging jets. The characteristic pressure of the gas in the disc will be equal to the ram pressure provided by the normal momentum flux of the jets. The gas pressure pushes the gas towards the geometrical center of the system and, at the same time, pushes it out of the plane of the disc.

As soon as the rotating gas, in its vertical expansion, goes beyond the jet width (in the vertical direction), i.e. to the area where there is no confining effect of the ram pressure, the gas starts expanding radially. Therefore, one can expect the formation of the flow pattern shown in Fig. 1b. Whether the rotating gas reaches the center, or not, depends on the viscosity and the ram pressure of the jets. In the situation shown in Fig. 1, the gas does reach the center and the rotating disc is formed. For a different jet aiming, with larger ϑ, a ring structure may form instead.

At low viscosity, the angular momentum conservation would lead to an increase of the angular frequency of the gas pushed towards the center. Conversely, at high viscosity, the rotation would occur in the rigid-rotor mode, the centripetal force near the center would decrease, and the gas would be pushed to the center, forming a disc-like structure. In other words, the role of viscosity is morphologically the same as in the real discs, where it allows the rotating matter to gradually progress towards the center. It will be a goal of the proposed experiment to find the magnitude of the turbulent viscosity, possibly affected by the presence of the magnetic field.

As was mentioned, on the way from the periphery of the disc to the center, the gas is also lost in the vertical direction. Therefore, in the system under consideration, the gas does not make more than of order one full revolution around the axis, before it moves upward or downward. This is a morphological difference from the astrophysical discs.

If the jets are generated by the irradiation of the front surface of the targets, the laser drive beams will be coming from directions oriented out of the plane of the disc, so that there will be no obscuration by the disc. If the jets are generated by radiating the targets from behind, as e.g. in Foster et al, 2002, 2005, then the obscuration problem goes away altogether.

3. Required energy

For rough estimates we will characterize the size of the central disc-like structure by a single parameter of the dimension of length, its radius *a*. The total thermal energy of this central "blob" will then be evaluated as $W_{Th} \sim (4\pi/3)a^3(3/2)p$, where p is the pressure and the gas is assumed to be monatomic. The rotation energy, for the rigid-rotor rotation, is $W_{Rot} \sim \left(4\pi a^3/3\right)\rho \mathrm{v}^2/5$, where ρ is the mass density of the central blob and v is the jet velocity. For a shallow intersection angle between the outer radial boundary of the disc and incoming jets, the rotation energy density at the periphery will be typically somewhat higher than the thermal energy, i.e., the gas at the periphery of the disc will be in the state of a supersonic rotation. On the other hand, near the axis, the thermal energy dominates. We parametrize the total energy in terms of the thermal energy, $W_{total} = W_{Th} + W_{Rot} \equiv (1+\xi)W_{Th}$. In all the subsequent estimates, we take $\xi \sim 1$. We note that, for for $\xi \sim 1$,

$$\mathrm{v} \sim \sqrt{2T(Z+1)/Am_p}\,, \tag{1}$$

where A is the atomic weight and m_p is the proton mass.

Assuming that the plasma of the central rotating object is fully ionized, one can write the following rough expression of its total energy

$$W_{Total} \sim (4\pi a^3/3)(3/2)(1+Z)(1+\xi)n_i T \sim 4\pi a^3(1+Z)n_i T\,, \tag{2}$$

or, numerically,

$$W_{Total}(kJ) = 1.75\times10^{-18}\left[a(mm)\right]^3(1+Z)n_i(cm^{-3})T(keV)\,. \tag{3}$$

This relation is illustrated in Fig. 2 for the case of carbon with T=0.3 keV.

In order for the disc to exist for the time of one revolution, $2\pi a/\mathrm{v}$, the duration of the experiment τ has to approach this value, or, according to Eq. (1),

$$\tau(ns) \sim 10a(mm)\sqrt{\frac{A}{(Z+1)T(keV)}}\,. \tag{4}$$

Evaluating the collisional kinematic viscosity of the plasma $\nu \sim \mathrm{v}_{Ti}\lambda_{ii}$, one can find the Reynolds number of the rotational flow, $\mathrm{Re} = a\mathrm{v}/\nu$. Using a convenient Eq (27) from Ryutov et al, 1999, one finds the following numerical expression:

$$\mathrm{Re} \sim 10^{-19}\frac{a(mm)Z^{9/2}n_i(cm^{-3})}{[T(keV)]^2} \tag{5}$$

As mentioned in Ryutov et al, 1999, Eq. (27) of that reference cannot be used for the fully ionized elements heavier than carbon.

Figure 2 shows that, for the plasma of 0.3 keV temperature, to obtain a disc with a Reynolds number exceeding 10^4, the required jet energy should be beyond 1 kJ, divided equally between 7 to 9 jets. According to Sec. 2, their angular divergence should be less than 30 – 40 degrees. According to Eq. (4), the duration of the experiment would be in the range of 10 ns. The laser pulse used to generate jets in the aforementioned laboratory experiments was typically shorter than 10 ns. However, on the way from the target to the merger area, the jets will be stretched due to the natural head-to-tail velocity variation, so that 10 ns duration of the disc is attainable.

For targets of lighter (lower Z) elements, like beryllium, the lower temperature is favored to keep viscosity low.

4. Role of radiation

For fully ionized target of relatively light elements like carbon, the radiative losses will be small. Radiation time for a fully stripped material is (Book, 1987)

$$\tau_{rad}(ns) \sim 5\times 10^{23}\frac{(Z+1)\sqrt{T(keV)}}{Z^3 n_i(cm^{-3})} \tag{6}$$

and for the case illustrated by Fig. 3 is much longer than the duration of the experiment. To study possible effects of radiation in the disc, one can consider adding small amounts of heavy elements. By "small" we mean that the additions are not significantly affecting the density and viscosity, but lead to a cooling of the disc material to the lower temperatures within the time shorter than one revolution time. The lower temperature would mean the lower viscosity, higher Reynolds number (as the momentum imparted to the disc will remain essentially unchanged), and higher Mach number.

5. Embedding and enhancing the magnetic field

The proposed geometry is amenable to introducing an external magnetic field that would be enhanced by the differential rotation of the disc. The geometry of the corresponding experiment is schematically illustrated by Fig. 3, where a cross-cut of the experiment by a vertical plane is presented. The cusp field coils are placed co-axially with the rotation axis. The coil design could be the same as that used with magnetized plasma experiments on the Omega laser facility (Gotchev et al, 2009). The difference is that the coils would have anti-parallel currents needed to generate the cusp geometry. At left and right targets are seen. They will be permeated by the magnetic field, whose duration should exceed the skin-time. For the targets of the 100 μm size made of plastic and foam this should not be a problem. The duration of the magnetic field created in Gotchev et al, 2009, was ~ 0.4 μs, enough to penetrate even through 100 μm thick copper.

The coils described in Gotchev et al, 2009 were capable of generating the magnetic field of up to 15 T. As the cusp system is somewhat different and had not been tested in the required environment, we assume that the field in the ring cusp, where the jet will originate, is ~ 5 T, i.e., lower than the field that could be reached in the case of parallel coil currents.

An interesting feature of the geometry shown in Fig. 3 is that each plasma jet is generated with the parallel (to the jet) magnetic field embedded in it. The jet carries this field to the area where it starts interacting to other jets, curls, merges with other jets and creates a toroidal field. This happens if the electrical conductivity of the plasma is high enough, so that the magnetic Reynolds number Re_M is much greater than 1.

We introduce Re_M by the equation $\mathrm{Re}_M = a\mathrm{v}/D_M$, where D_M is the magnetic diffusivity. Using the numerical estimate (19) from Ryutov et al, 2000, we find:

$$\mathrm{Re}_M \sim 10^4 \frac{a(mm)[T(keV)]^2}{Z}\sqrt{\frac{Z+1}{A}} \tag{7}$$

In the parameter domain covered by Fig. 2 it is larger than unity (e.g., for a=0.3 mm, carbon, T=0.3 keV) it is ~ 100. In other words, the field will be strongly coupled with the plasma, making the system particularly interesting for the studies of the field amplification by sheared flows and, in the turbulent regimes, the field evolution in a turbulent fluid.

To get some rough estimate of the possible dynamical effect of the magnetic field on the disc motion, we introduce a standard parameter β, the ratio of the plasma pressure to the magnetic pressure. This parameter can be evaluated numerically as

$$\beta \sim 4\times 10^{-16}\frac{(Z+1)n_i(cm^{-3})T(keV)}{\left[B(T)\right]^2} \tag{8}$$

The plot of the parameter β vs the plasma temperature for several values of the plasma energy W_{Total} is presented in Fig. … .One can see that, for the parameters mentioned in Sec. 3, the magnetic field of 5T cannot play a significant dynamical role unless it is strongly enhanced by a differential rotation in the disc. On the other hand, if the field is enhanced by a factor of 5, it may already become dynamically-significant (Fig. 4).

6. Discussion

We have shown that, by merging of a modest number of jets (6-9) one can imitate disc structures met in astrophysics. The radial confinement of the disc is provided by the ram pressure of the incoming jets; as the disc plasma is not confined in the axial direction, a bipolar outflow will be formed. With the energy per jet in the range of 30 – 100 J one can create the plasma where the Reynolds number will exceed 10^4, this meaning that the shear-flow turbulence will develop and will affect the radial transport of the angular momentum. This is an important aspect of the accretion disc physics.

Even more interesting is the fact that the geometry shown in Fig. 1 is amenable to the introduction of the magnetic field which can be enhanced by the shear-flow in the disc. The magnetic Reynolds number in the range of 10 to 100 are achievable, so that the magnetic field will be strongly affected by the plasma flow. By increasing the bias magnetic field, one can reach the regimes where even a modest enhancement of the initial magnetic field frozen in the jets at their origin would be sufficient to have a dynamical impact on the disc.

The total energy of all jets is in the range of 300 J – 1 kJ. Accounting for possible inefficiencies, this would require a laser facility with the total energy (split between 6 to 9 beams) in the range of a few kJ. The total duration of the experiment should be in the range from 5 ns to 30 ns.

For the disc of the radius of 0.3 -1 mm, the embedded magnetic field can be detected by the proton deflectometry, with the probing proton beams generated either by the electrostatic ion acceleration from a thin foil (e.g., Snavely et al, 2000) or by imploding an auxiliary fusion capsule (Li et al, 2009). In the latter case, the use of a larger-scale laser facility (like Omega) is needed.

The experiment will provide a lot of flexibility: the Reynolds number and the magnetic Reynolds number can be varied in a broad range; the bias magnetic field can be changed as desired; the radiation losses can be controlled by the amount of heavy impurities added to the targets. All this may lead to developing an experimental platform suitable for validation and verification of the numerical codes used to simulate accretion discs in astrophysics.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

Abramowicz M., Bjornsson G., Pringle J.E. Eds. (1998) "Theory of black hole accretion disks." Cambridge University Press.

Balbus S.A. (2003), "Enhanced Angular Momentum Transport in Accretion Disks", Annu. Rev. Astron. Astrophys. 41: 555–597.

Book D.L. (1987) "NRL Plasma Formulary." *Naval Research Laboratory*.

Farley D.R., Estabrook KG, Glendinning SG, et al. (1999) PRL, **83**, 1982.

Foster, J.M., Wilde B.H., Rosen P.A., et al. (2002). Phys. Plas. **9**, 2251.

Foster, J.M., Wilde B.H., Rosen P.A., et al. (2005), ApJ, **634**, L77.

Frank, J. , King, A., Raine, D., (2002). "Accretion power in astrophysics" (Third ed.). Cambridge University Press. ISBN 0-521-62957-8.

Gotchev O.V., Knauer J.P., Chang P.Y., et al. (2009). Rev. Sci. Instrum. **80**, 043504.

Gregory C.D., Loupias B., Waugh J., et al. PPCF, **50**, 124039 (2008).

Li C. K., Seguin F.H., Frenje J. A., et al. (2009) Phys. Plas. **16** 056304

Nicolai P, Tikhonchuk V.T., Kasperczuk A., et al. (2006) Phys. Plas, **13**, 062701.

Remington, B.A., Drake, R.P., Ryutov, D.D. *Rev. Mod. Phys.,* **78,** 755, 2006.

Ryutov, D.D., Drake, R. P., Kane, J., et al Astrophysical Journal, **518**, p. 821 (1999).

Ryutov, D.D., Drake, R. P., Remington B.A. Astrophysical Journal - Supplement, **127**, 465 (2000).

Shigemori K., Kodama R., Farley D. R., et al. PRE **62**, 8838 (2000)

Snavely RA, Key MH, Hatchett SP, et al. PRL, **85**, 2945 (2000)

M. Thompson (2006). An introduction to astrophysical fluid dynamics. Imperial College Press, Chapters 8-9.

Tikhonchuk VT, Nicolai P, Ribeyre X, et al. (2008) PPCF, **50**, 124056

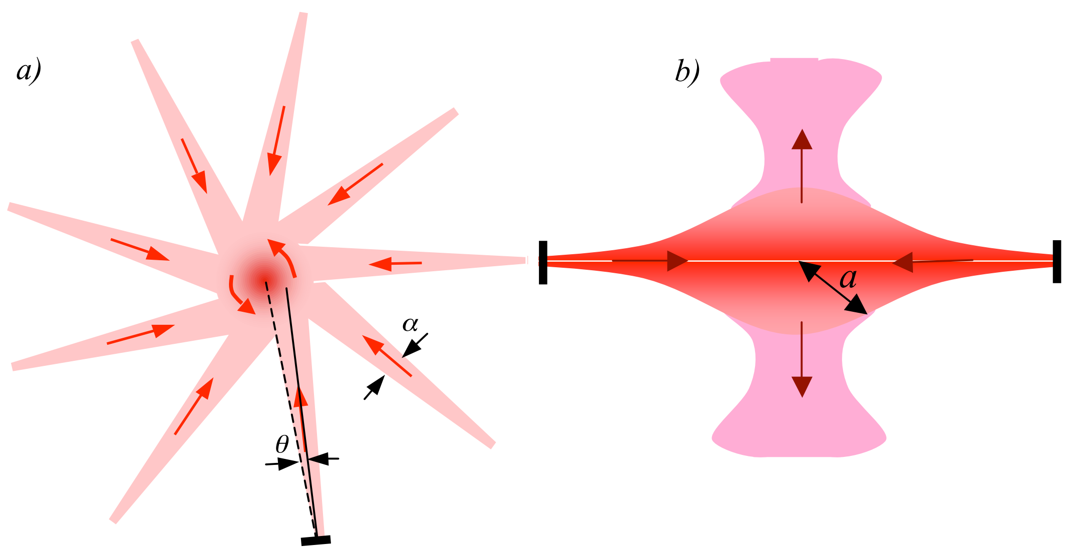

Fig. 1 The geometry of the array. a) A top view of the array of 9 jets. The direction of a jet differs from the direction to the geometrical center of the system (dashed line) by the angle θ; the angular divergence of the jet is α. The figure corresponds to $\theta \approx \alpha/2$, but in the general situation this condition can be different. Shown by a short fat line is the position of one of the targets. Actual shape of the targets can be different from planar. b) Side view of the array. Arrows indicate direction of the poloidal flow: toward the center and then to the funnel-like outflow.

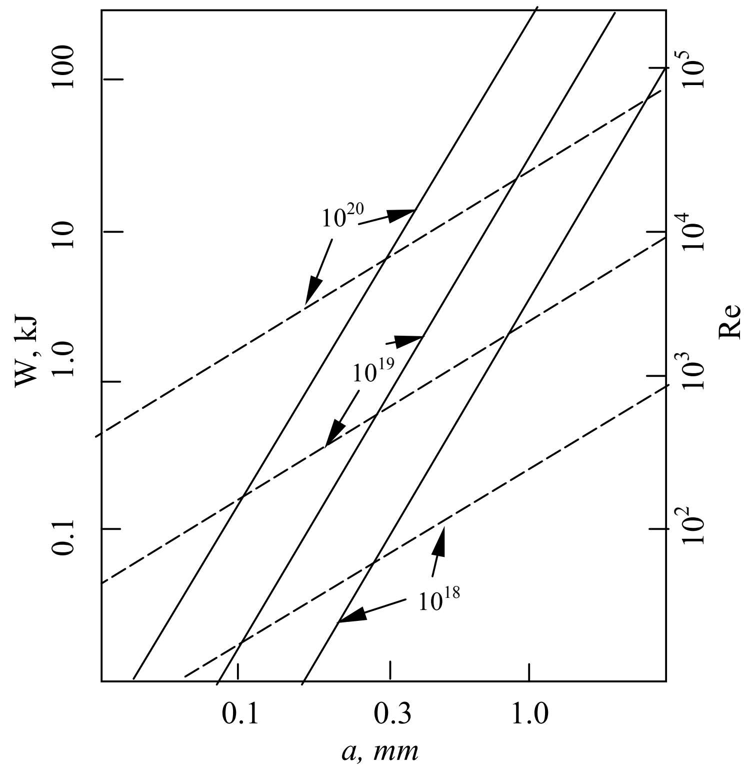

Figure 2. The energy of the rotating disc (solid lines, left scale) and Reynolds number (dashed lines, right scale) vs the disc radius *a*. The numbers by the cureves correspond to the ion density. The temperature is 300 eV, carbon.

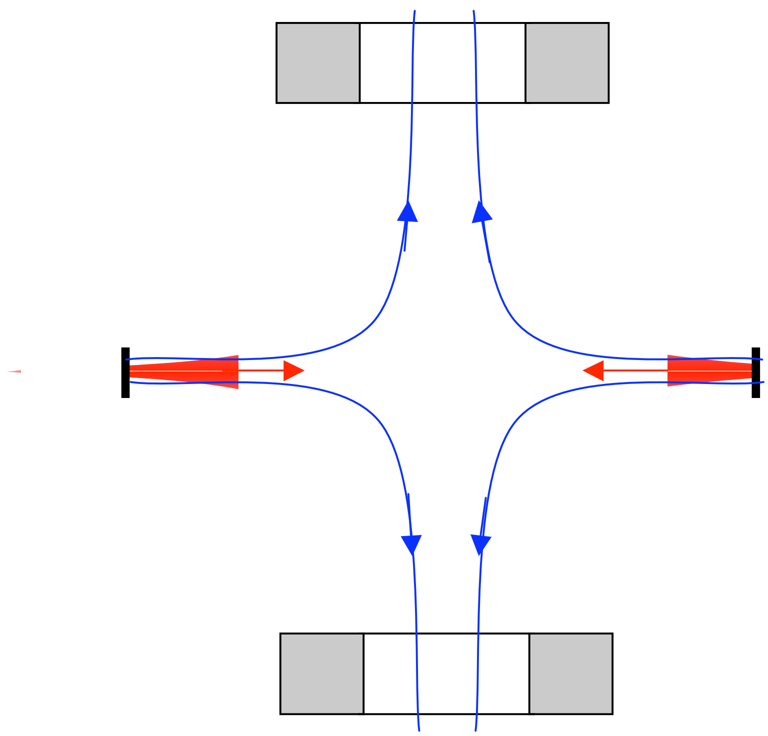

Fig. 3 Magnetization of jets in a cusp geometry. Shown are two coils with the oppositely directed currents. They create a cusp magnetic field with the vacuum field lines shown in blue. The jets are shown at the early stage of their generation on the targets, when they still haven't reached the merging area. The magnetic field is frozen into the jet plasma at its origin and will be coiled together with the jets.

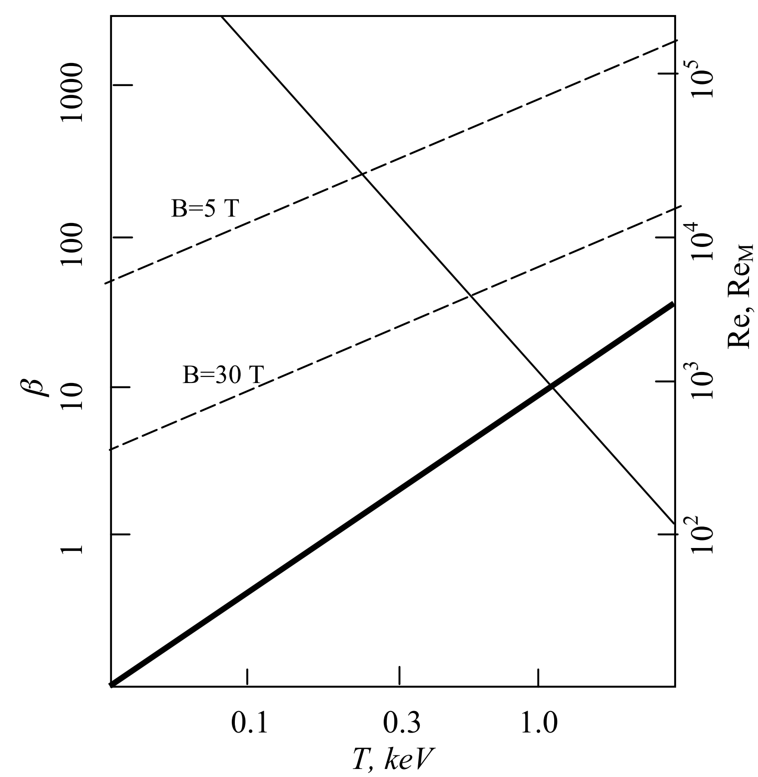

Figure 4 The dimensionless characteristics of the rotating disc vs the plasma temperature (carbon, a=0.3 mm, n_i=10^{19} cm^{-3}): dashed lines – plasma beta; bold line – Re_M; thin line – Re.